

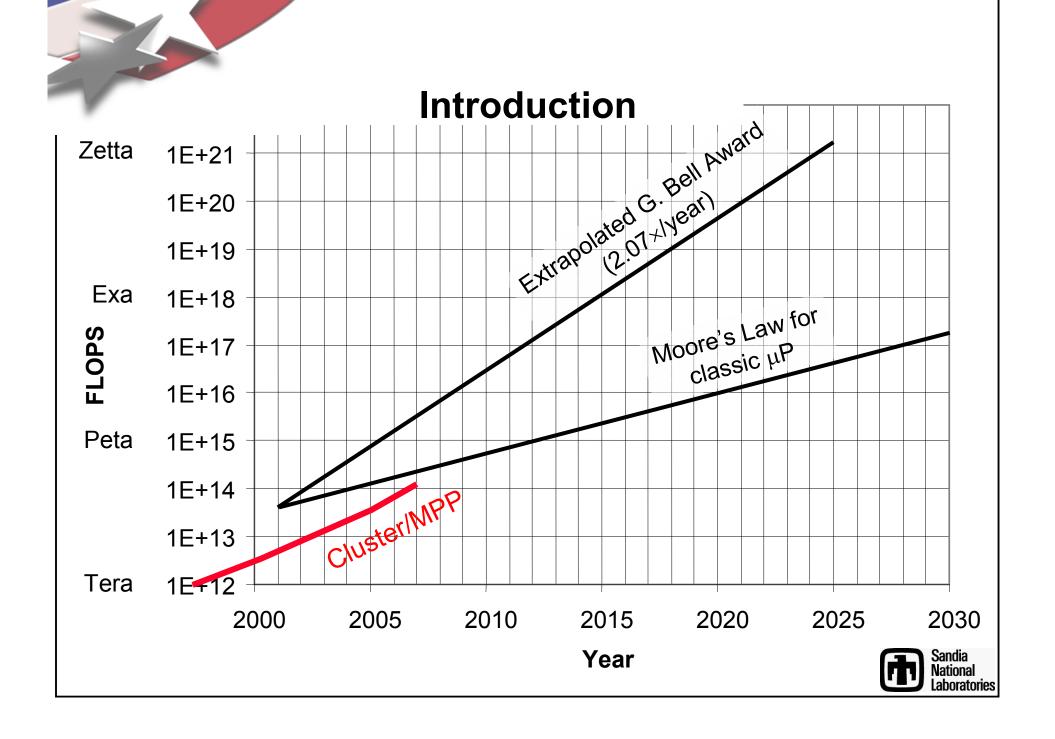
Matching Supercomputing to Progress in Science

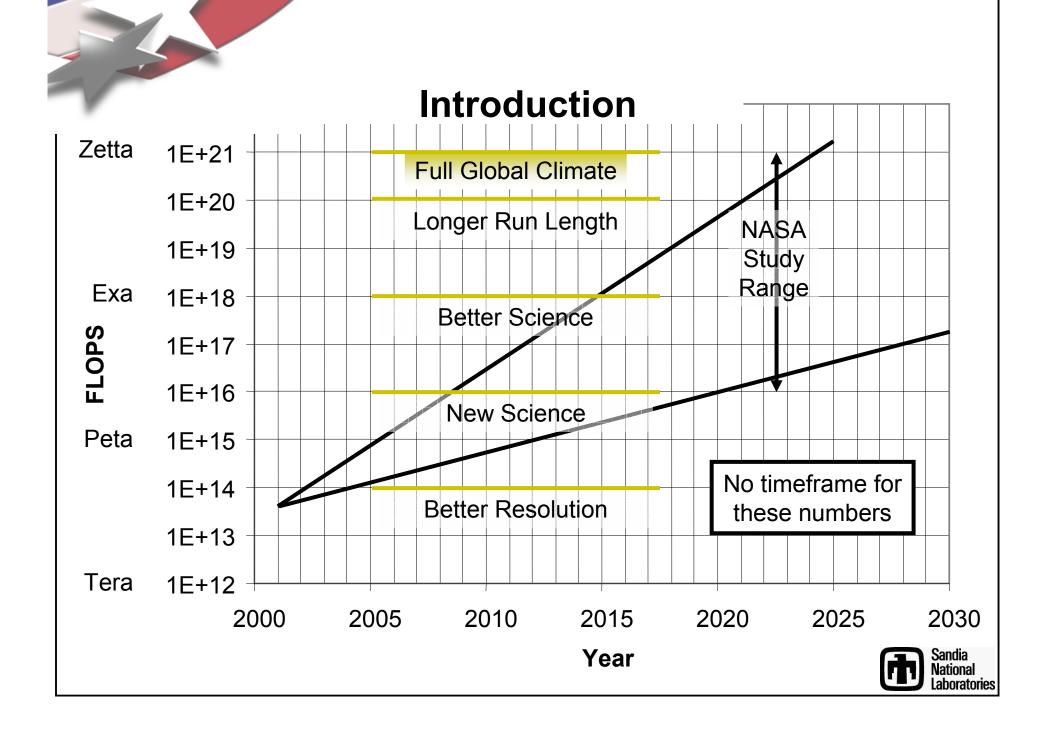
Erik P. DeBenedictis

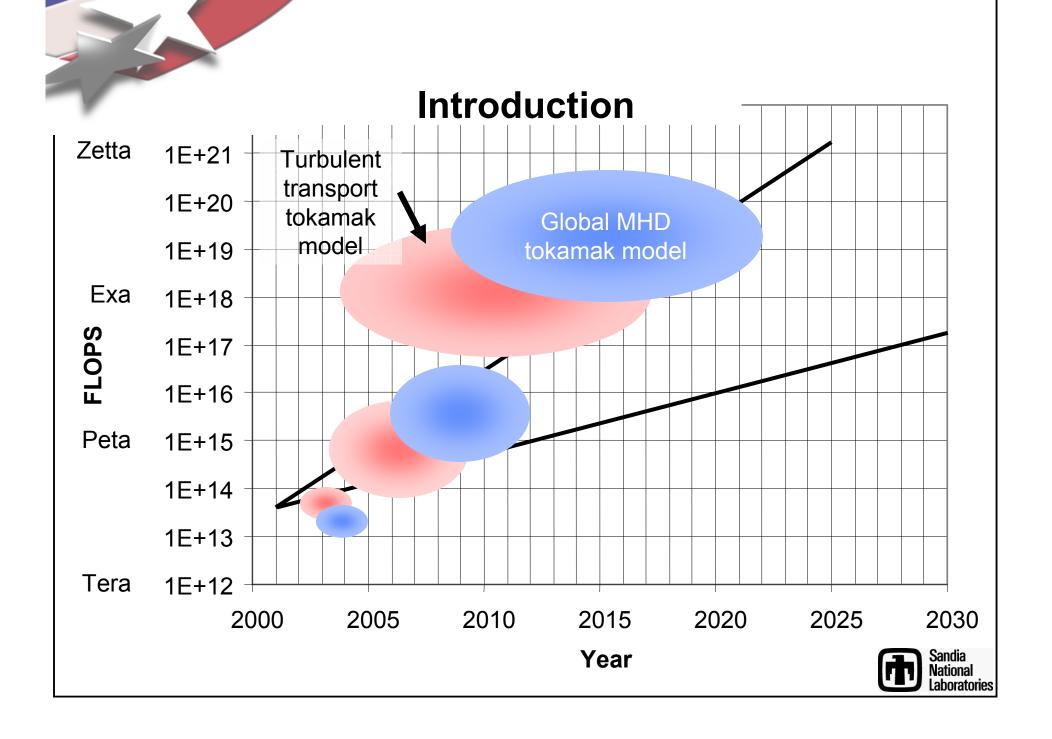
Sandia National Laboratories SAND2004-3333P

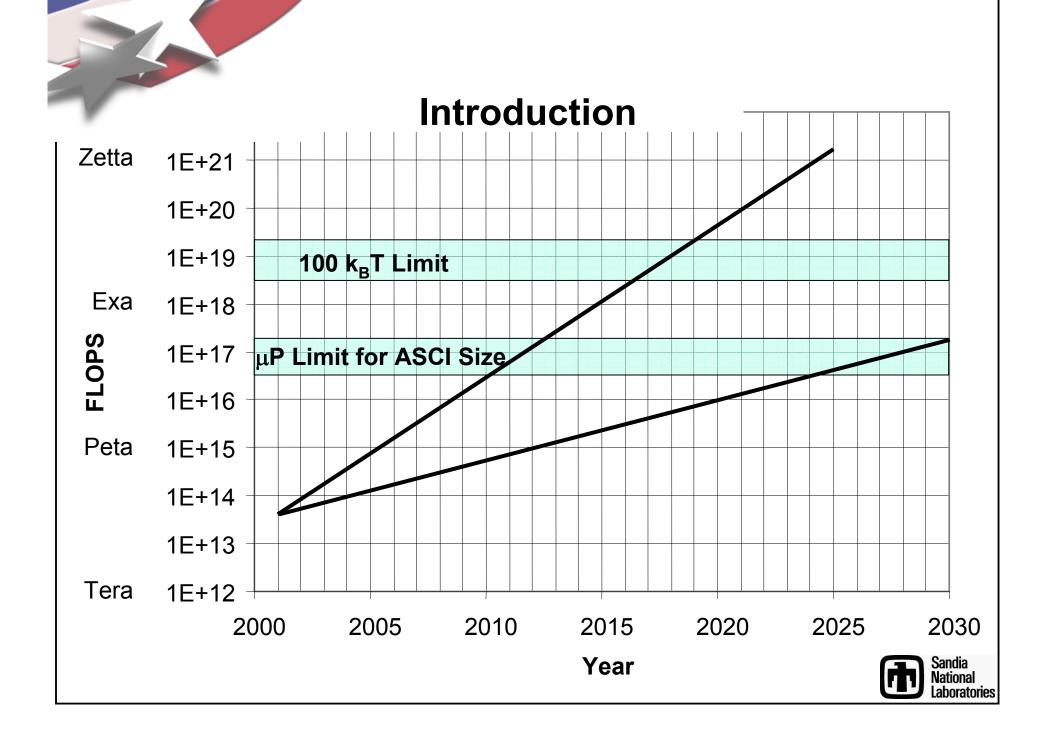


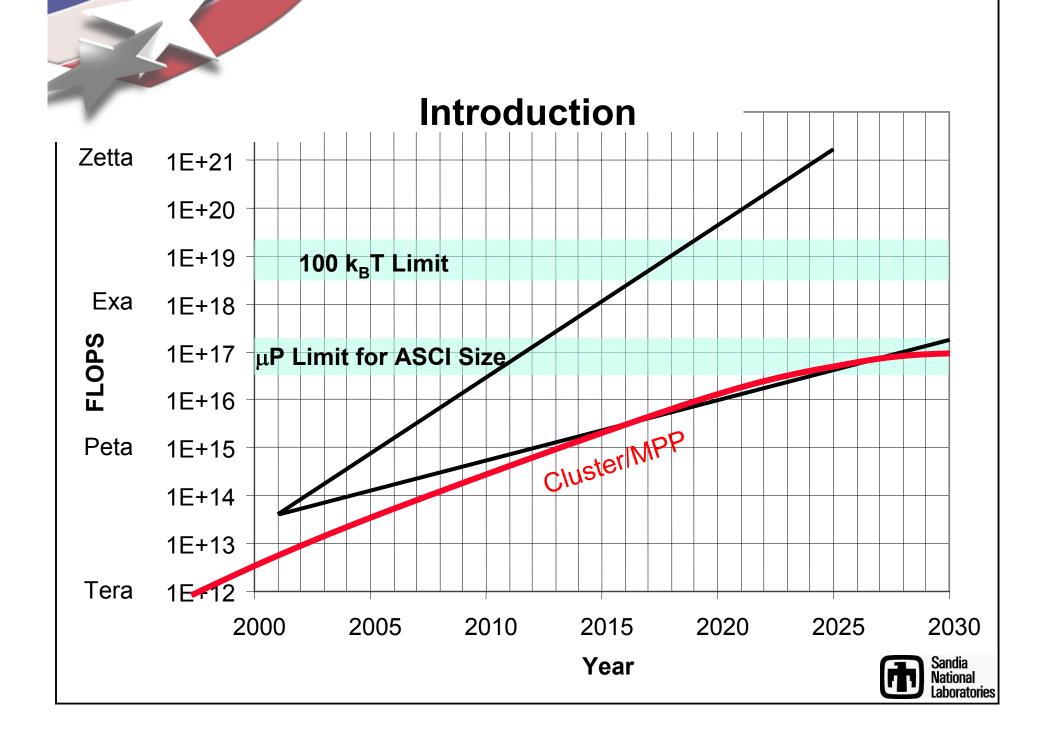


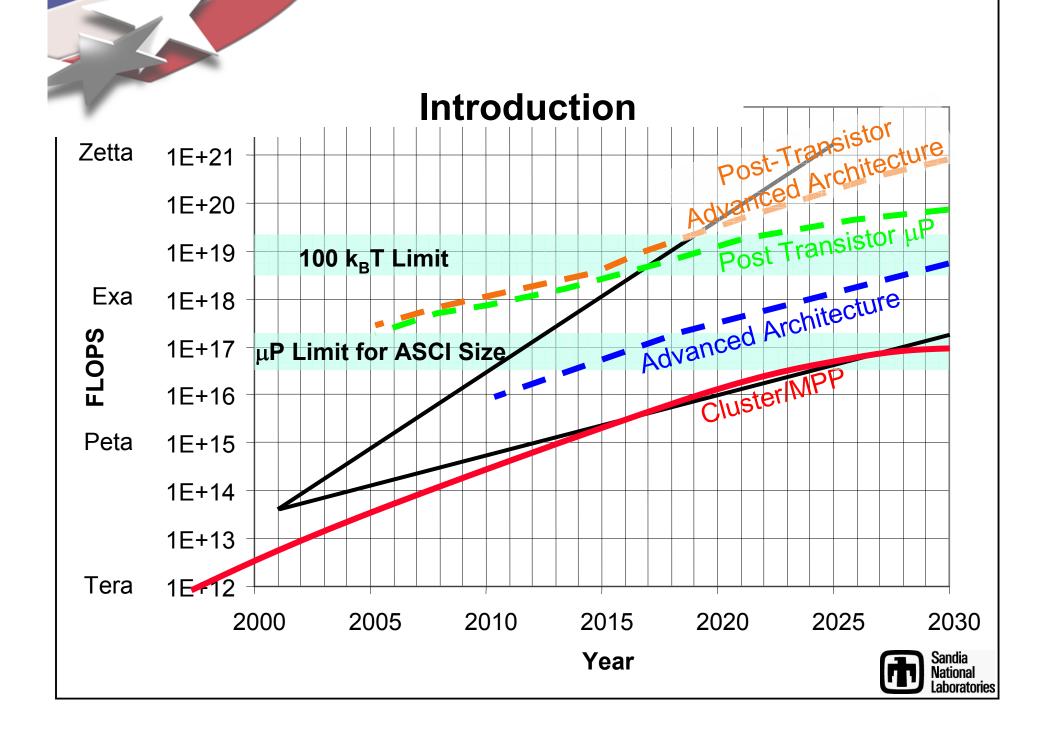


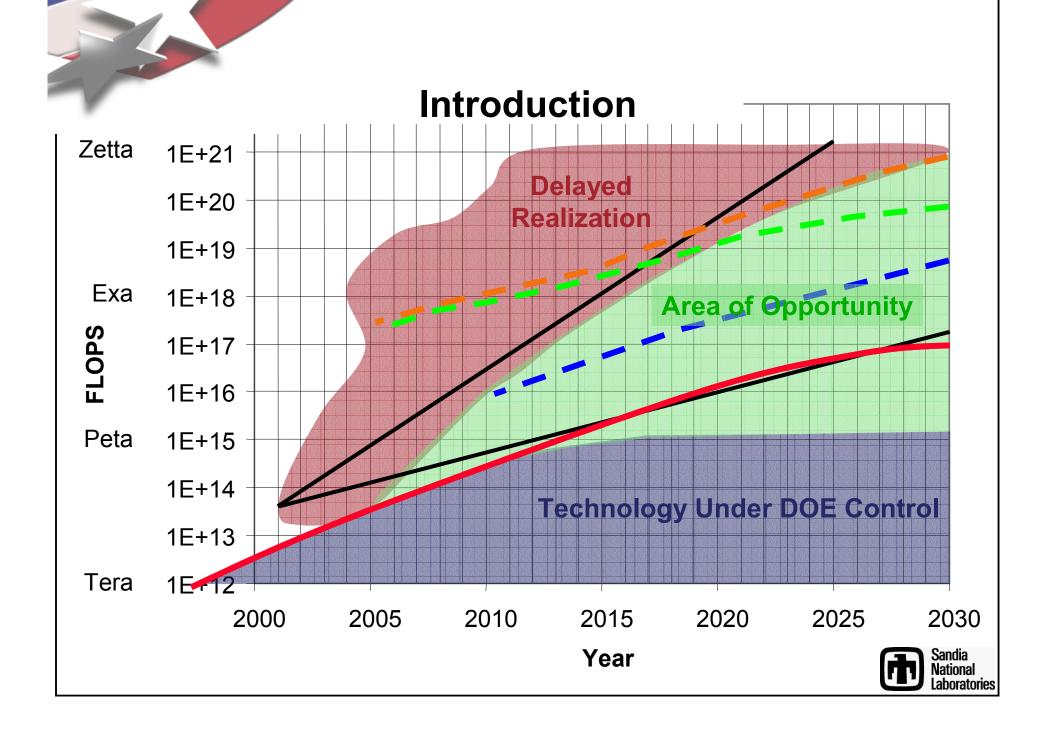














Outline

- Applications of the Future
- Limits of Moore's Law
- An Expert System/Optimizer for Supercomputing
- Reaching to Zettaflops
- Roadmap and Future Directions





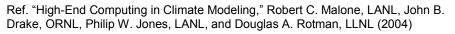
Global Climate

- Objective
 - Collect data about Earth
 - Model climate into the future
 - Provide "decision support" and ability to "mitigate"
- Approaches
 - Climate models exist, but need they more resolution, better physics, and better initial conditions (observations of the Earth)
- Computer Resources Required
 - Increments over current workstation on next slide



FLOPS Increases for Global Climate

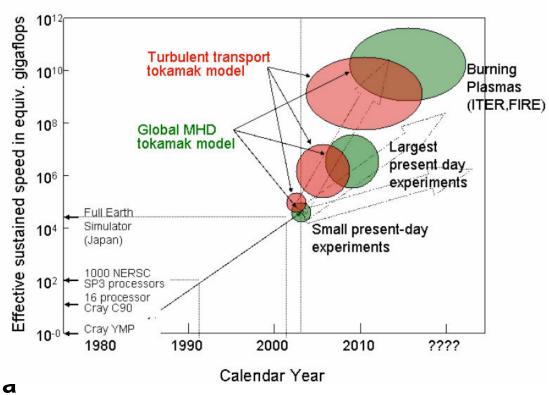
	Issue	Scaling
1 Zettaflops	Ensembles, scenarios 10×	Embarrassingly Parallel
100 Exaflops	Run length 100×	Longer Running Time
1 Exaflops ←	New parameterizations 100×	More Complex Physics
10 Petaflops	Model Completeness 100×	More Complex Physics
100 Teraflops	Spatial Resolution 10 ⁴ × (10 ³ ×-10 ⁵ ×)	Resolution
10 Gigaflops ←	 Current	





Requirements for Plasma Simulation

- Very high peak perform ance requirements
 - but seeking algorithmic improvements
- Two methods
 - Red regions very scalable, Monte Carl
 - Green regions N⁴ scaling (FEM)
- Long term objective
 - Merge methods into a single code



Ref. "Plasma Science Contribution to the SCaLeS Report," S.C. Jardin, October 2003





NASA Climate Earth Station

Based on these inputs, various portions of the Modeling and Data Assimilation System will require anywhere from 10⁷ to 10¹³ GFLOPS of computational resources. In other words, the range of computational resources needed is 10¹⁶ to 10²¹ Floating Point Operations per Second. For the curious, the range can also be stated as 10 PetaFLOPS to 1 ZettaFLOPS.

4.1.2. Anticipated Computing Technology Capabilities

At first glance, the numbers discussed in the previous section appear so high as to be impossibly ludicrous. However, with the expected growth in computing capabilities, the lower end of this spectrum actually falls within the domain of possibility.

"Advanced Weather Prediction Technologies:
 NASA's Contribution to the Operational Agencies,"
 Gap Analysis Appendix, May 31, 2002





NASA Work Station

- "...the ultimate goal of making the computing underlying the design process so capable that it no longer acts as a brake on the flow of the creative human thought..."
- Requirement 3 Exaflops
- Note: In the context of this report, this requirement is for one or a few engineers, not a supercomputer center!

NASA/TM-1999-209715



Compute as Fast as the Engineers Can Think!

ULTRAFAST COMPUTING TEAM FINAL REPORT

R. T. Biedron, P. Mehrotra, M. L. Nelson, F. S. Preston, J. J. Rehder, J. L. Rogers, D. H. Rudy, J. Sobieski, and O. O. Storaasli Langley Research Center, Hampton, Virginia





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*** This is a Preview ***

	Best-Case Logic	Microprocessor Architecture	,	Physical Factor	Source of Authority
	1.5 Yottaops			Landauer limit 600KW/(100k _B T)	Esteemed physicists
				Derate 20,000 convert logic ops to floating point	Floating point engineering (64 bit precision)
Expert Opinion	100 Exaflops ← 125	800 Petaflops i:1 →		Derate for manufacturing margin (4×)	Estimate
Estimate	25 Exaflops	200 Petaflops		Uncertainty (6×)	Gap in chart
	4 Exaflops	32 Petaflops	*	Improved devices (4×)	Estimate
	1 Exaflops	8 Petaflops		•	ITRS committee of experts
•	: Supercomputer	90 Taraflana		improvement to 22 nm (100×)	
\$100M bud	st of Red Storm: get; consumes	80 Teraflops		Lower supply voltage (2×)	ITRS committee of experts
1.8 MW wa to active co	II power; 600 KW mponents	40 Teraflops	←	Red Storm	contract
					Sani Nati Labo



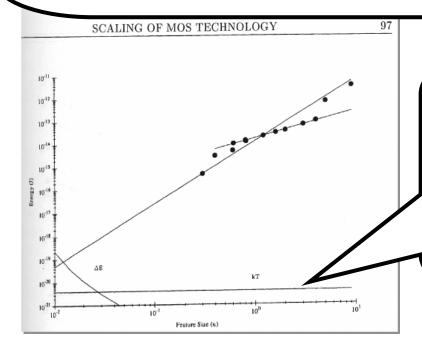
Thermal Noise Limit

This logical irreversibility is associated with physical irreversibility and requires a minimal heat generation, per machine cycle, typically of the order of kT for each irreversible function.

Increverability and Heat Generation
In the Computing Process

In space for accounts quadrant variable verbal exists ofth patent signly fundamental to space for accounts on the control of the patent signly fundamental to the control of the control

National



R. Landauer 1961

kT "helper line," drawn out of the reader's focus because it wasn't important at the time of writing

Carver Mead, Scaling of MOS Technology, 1994

Metaphor: FM Radio on Trip to Sacramento

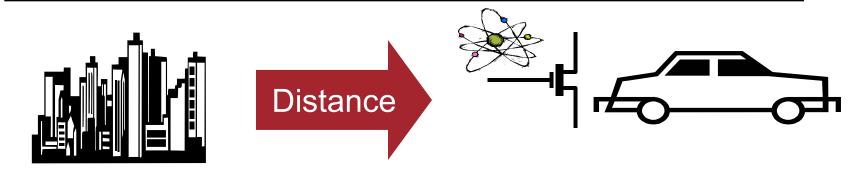
- You drive to Sacramento listening to FM radio
- Music clear for a while, but noise creeps in and then overtakes music
- Why?
 - Signal at antenna weakens
 - Thermal electron noise constant at k_B T

- Analogy: You live out the next dozen years buying PCs every couple years
- Electrical effect
 - Moore's Law causes switching energy of gates to decrease at about 30% per year
 - Thermal electron noise constant at k_B T

Details: Erik DeBenedictis, "Taking ASCI Supercomputing to the End Game," SAND2004-0959



FM Radio and End of Moore's Law



Driving away from FM transmitter→less signal Noise from electrons → no change



Increasing numbers of gates → less signal power Noise from electrons → no change



Amount of Reliability Needed

- We expect computers to be reliable
- A future supercomputer will perform 10³⁰-10⁴⁰ operations in its lifetime
- Error rate should be < 10⁻³⁰
 10⁻⁴⁰
- Reliability due to thermal noise about e^{-E/kt}
- Need about e⁻¹⁰⁰ error rate, or 100 k_BT switching energy

SNR (db)	Power Ratio	P _{error}
10	10	3.9×10 ⁻⁶
14	25	6.8×10 ⁻¹³
18	63	1.4×10 ⁻²⁹
22	160 Noise Lim	3.3×10 ⁻⁷¹
26	400	1.8×10 ⁻¹⁷⁵
30	1,000 2016	4.5×10 ⁻⁴³⁷
34	2,500	7.1×10 ⁻¹⁰⁹⁴
38	6,300	2.2×10 ⁻²⁷⁴³
42	16,000	1.8×10 ⁻⁶⁸⁸⁶
46	40,000	3.8×10 ⁻¹⁷²⁹³
50	100,000 Today	3.2×10 ⁻⁴³⁴³³
54	250,000	8.1×10 ⁻¹⁰¹⁹⁴
58	630,000	1.8×10 ⁻²⁷⁴⁰²⁵
62	1,500,000	9.6×10 ⁻⁶⁸⁸³¹⁵

$$q := \int_{t}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx; t \to \sqrt{2 * 10^{\frac{50x}{10}}}$$





Noise Levels

- 0 db Limit of hearing
- 20 db Rustling leaves
- 40-50 db Typical neighborhood
- 60-70 db Normal conversation
- 80 db Telephone dial tone
- 85 db City traffic inside car
- 90 db Train whistle @500'
- 95 db Subway train @200'
- 90-95 db Ear damage

- Today: 50 db
 - Thermal noise:Logic::Rustling leaves:Talking
- 2016: 30 db
 - Thermal noise:Logic:: Talking:Train Whistle
- Reliability limit 20 db
 - Thermal noise:Logic::Outsideneighborhood:Talking



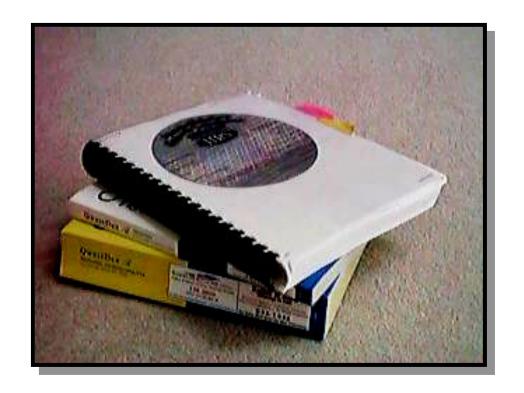
Personal Observational Evidence

- Have radios become better able to receive distant stations over the last few decades with a rate of improvement similar to Moore's Law?
- You judge from your experience, but the answer should be that they have not.
- Therefore, electrical noise does not scale with Moore's Law.





- Generalization of Moore's Law
 - Projects many parameters
 - Years through 2016
 - Includes justification
 - Panel of experts
 - known to be wrong
 - Size between
 Albuquerque white and yellow pages





Semiconductor Roadmap

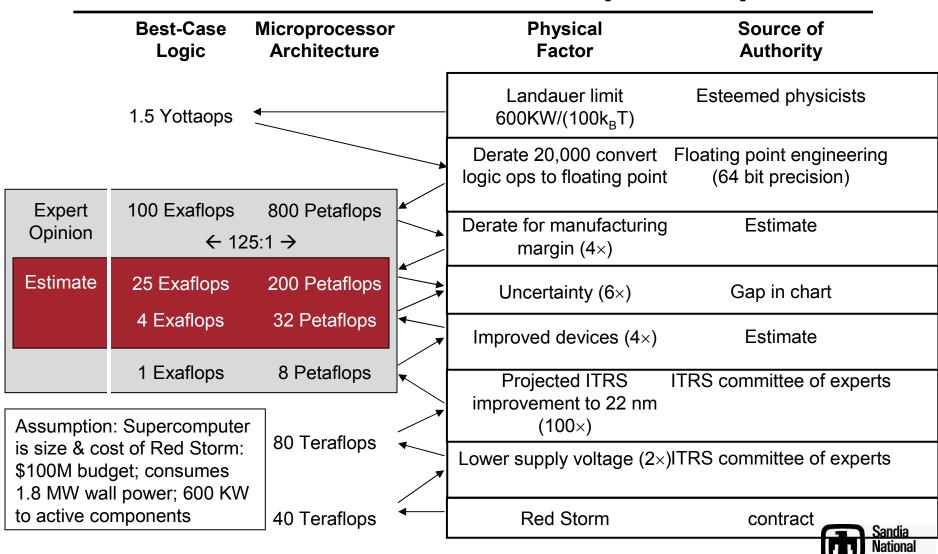
YEAR OF PRODUCTION	2010	2013	2016
DRAM ½ PITCH (nm)	45	32	22
MPU / ASIC ½ PITCH (nm)	50	35	25
MPU PRINTED GATE LENGTH (nm)	25	18	13
MPU PHYSICAL GATE LENGTH (nm)	18	13	9
Physical gate length high-performance (HP) (nm) [1]	18	13	9
Equivalent physical oxide thickness for high-performance T_{ox} (EOT)(nm) [2]	0.5-0.8	0.4-0.6	0.4-0.5
Gate depletion and quantum effects electrical thickness adjustment factor (nm) [3]	0.5	0.5	0.5
T_{ox} electrical equivalent (nm) [4]	1.2	1.0	0.9
Nominal power supply voltage (V_{dd}) (V) [5]	0.6	0.5	0.4
Nominal high-performance NMOS sub threshold leakage current, $I_{sd,leak}$ (at 25 ° C) (μ A/ μ m) [6]	3	7	10
Nominal high-performance NMOS saturation drive current , I_{dd} (at V_{dd} at 25 ° C) ($\mu A/\mu m$) [7]	1200	1500	1500
Required percent current-drive "mobility/transconductance improvement" [8]	30%	70%	100%
Parasitic source/drain resistance (Rsd) (ohm 100) 502	110	90	80
arasitic source/drain resistance (Rsd) pe arasitic capacitance percent of ideal gat	25%	30%	35%
	31%	36%	42%
High-performance NMOS device τ (C _{gate} * V_{dd}/I_{dd} -NMOS)(ps) [12]	0.39	0.22	0.15
Relative device performance [13]	4.5	7.2	10.7
Energy per (W/L _{gate} =3) device switching transition ($C_{gate}*(3*L_{gate})*V^2$) (fJ/Device) [14]	0.015	0.007	0.002
Static power dissipation per (W/Lgate=3) device (Watts/Device) [15]	9.7E-08	1.4E-07	1.1E-07

White—Manufacturable Solutions Exist, and Are Being Optimized Yellow—Manufacturable Solutions are Known Red—Manufacturable Solutions are NOT Known





Limits for a \$100M-Class Supercomputer





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Expert System for Future Supercomputers

- Applications Modeling
 - Runtime T_{run} = f₁(n, design)
- Technology Roadmap
 - Gate speed = f_2 (year),
 - chip density = f_3 (year),
 - $-\cos t = (n, design), ...$
- Scaling Objective Function
 - I have \$C₁ & can wait T_{run}=C₂ seconds. What is the biggest n I can solve in year Y?

 Use "Expert System" To Calculate:

Max n: $\$< C_1$, $T_{run} < C_2$ All designs

Report:

Floating operations

T_{run}(n, design)

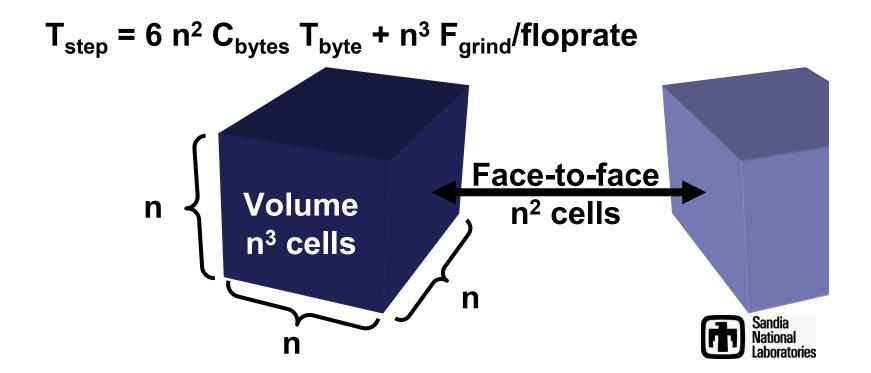
and illustrate "design"



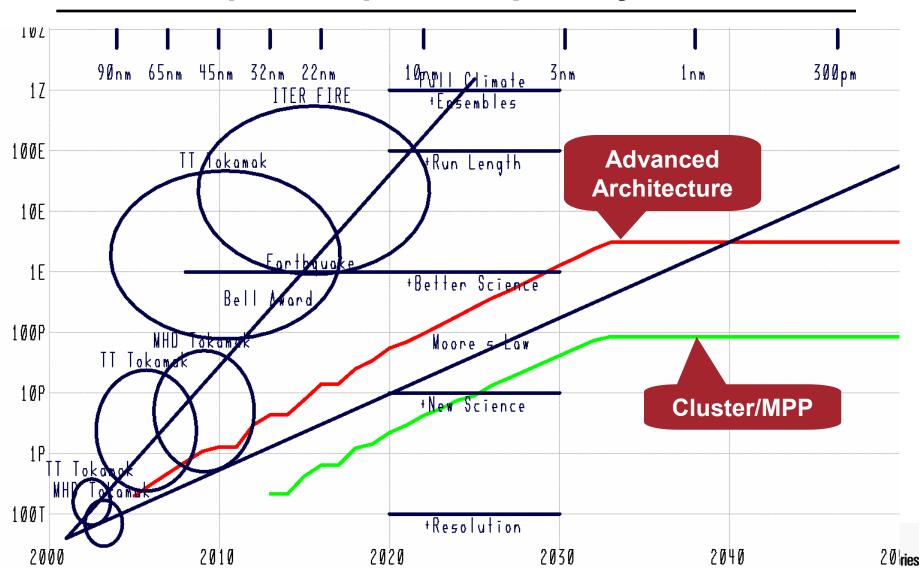


- Simple case: finite difference equation
- Each node holds n×n×n grid points

- Volume-area rule
 - Computing ∞ n³
 - Communications ∞ n²



Supercomputer Expert System

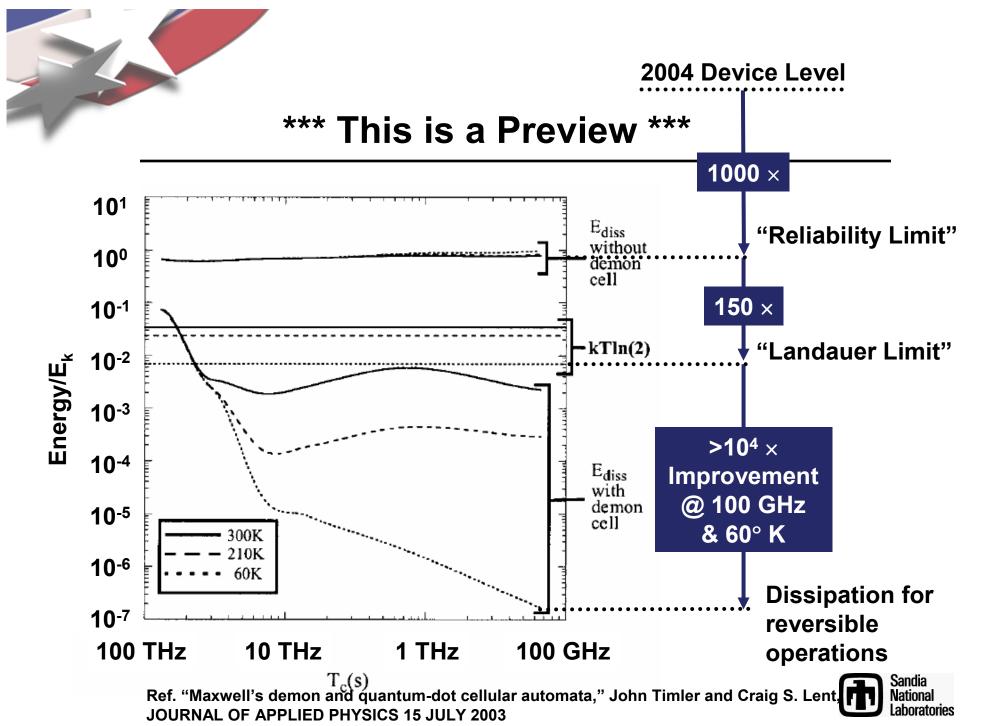




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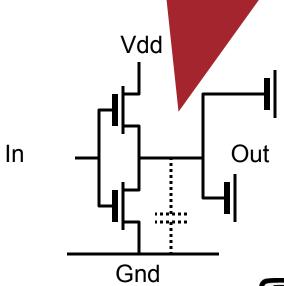




Today's Universal Logic & Reliability Limit

- Today's logic operates on a simple principle
 - Create a "1" by taking charge from the positive supply
 - Create a "0" by sending charge to the negative supply
- Energy Consumption
 - Each gate switch generates $E_{sw} = \frac{1}{2} \text{ CV}^2 > \frac{100 \text{ k}_B \text{T}}{2}$

Signal energy must be greater than ~100 k_BT to avoid spontaneous glitches. To change a bit, convert energy to heat.



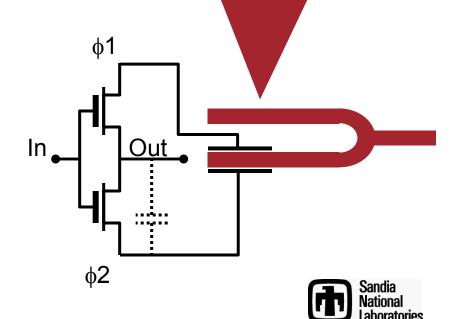




"Recycling" Power

- The 100k_BT limit appears unbeatable, but the energy can be "recycled"
- Diagram shows a "SCRL" circuit with regular transistors
- Power comes through a largely loss less resonant device (tuning fork)
- No apology offered for the mechanical device; this is the price of progress

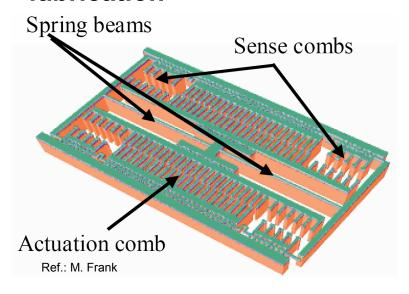
Signal energy must be greater than ~100 k_BT to avoid spontaneous glitches. However, signal energy is recycled by tuning fork



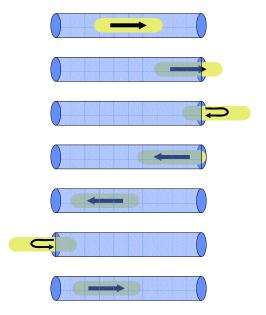


Resonant Clocks

- Tuning Fork
 - Nice idea but slow
- MEMs Resonator
 - Moderate speed and compatible with silicon fabrication



- Carbon Nanotube
 - Simulated to 50 GHz but not known how to fabricate at present







Landauer's Arguments

- Landauer makes three arguments in his 1961 paper
 - Kintetics of a bistable well (next slide)
 - Entropy generation →

Sorry, I don't have a cute story (like the FM radio) for Landauer's argument

 Entropy of a system in statistical mechanics:

$$S = k_B \log_e(W)$$

W is number of states

 Entropy of a mechanical system containing a flip flop in an unknown state:

$$S = k_B \log_e(2W)$$

After clearing the flip flop:

$$S = k_B \log_e(W)$$

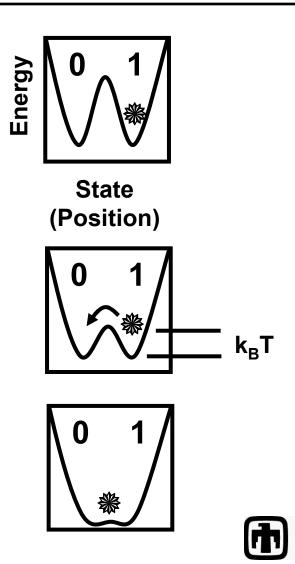
Difference k_B log_e(2)





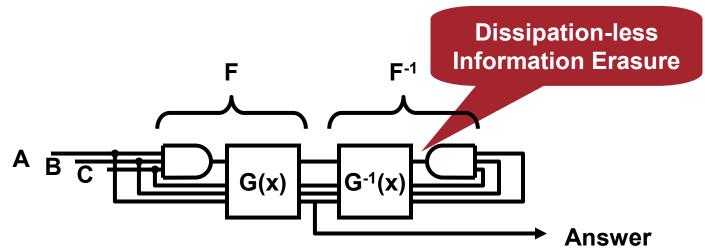
Landauer's Limit

- The Landauer limit says you can reduce power dissipation for irreversible functions below 100 k_BT, but not below k_BT log_e2
- In the diagram on the right, when the energy barrier drops to below about k_BT, the state will spontaneously switch and dissipate remaining energy as heat



Reversible Logic Can Beat Landauer's Limit

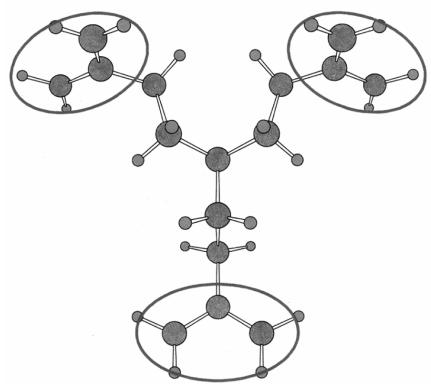
- Any function can be made reversible by saving its inputs
- Diagram below outlines an asymptotically zeroenergy way to perform the AND function, in composition with other logical operations

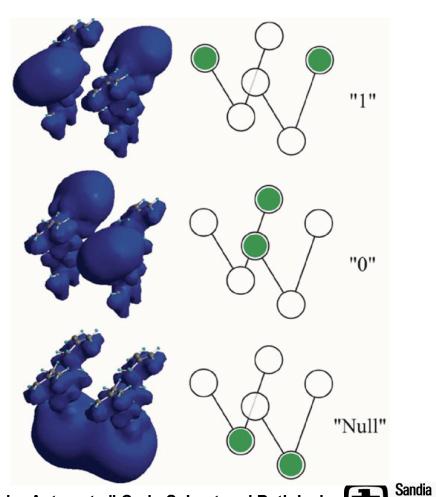




A New Computing Device: Quantum Dots

 Pairs of molecules create a memory cell or a logic gate





National

Ref. "Clocked Molecular Quantum-Dot Cellular Automata," Craig S. Lent and Beth Isakse IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 50, NO. 9, SEPTEMBER 2003

Upside Potential of Quantum Dots

THE RESERVE OF THE PARTY OF

Manwell's demon and quantum-dot cellular automata

Arts Tories and Couly & $\tan^{2}\theta$. By several of the class, then then, below 0.01(Contract Ferrage 1990), was great in April 1990).

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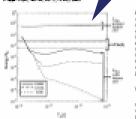
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Next Slide

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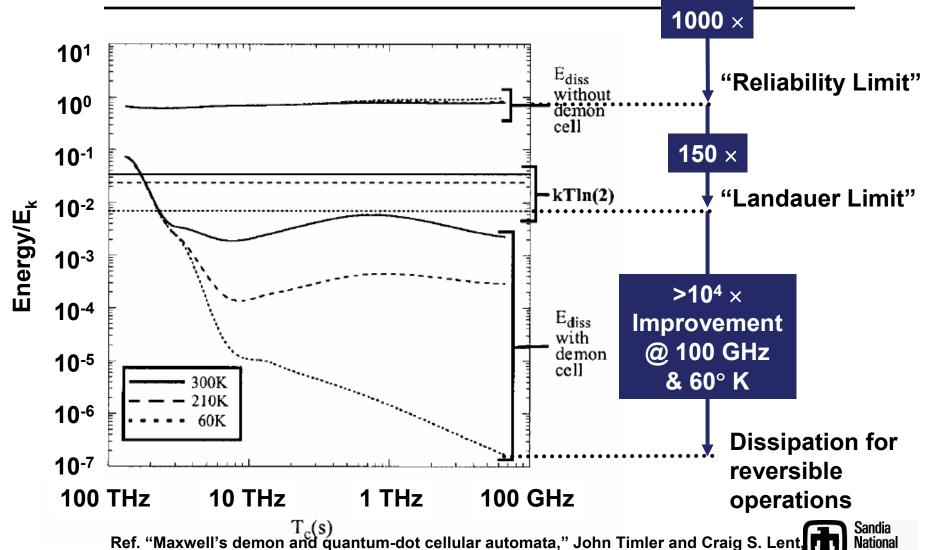
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Laboratories

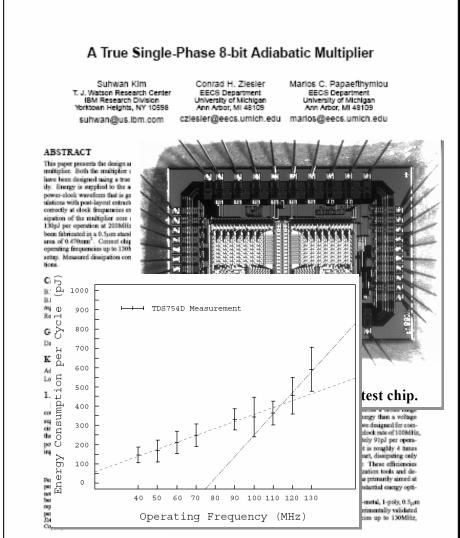
Upside Potential of Quantum Dots



 $T_{\rm c}(s)$ Ref. "Maxwell's demon and quantum-dot cellular automata," John Timler and Craig S. Lent, **JOURNAL OF APPLIED PHYSICS 15 JULY 2003**



- 8×8 Multiplier Designed, Fabricated, and Tested by IBM & University of Michigan
- Power savings was up to 4:1



Reversible Microprocessor Status

Status

- Subject of Ph. D. thesis
- Chip laid out (no floating point)
- RISC instruction set
- C-like language
- Compiler
- Demonstrated on a PDE
- However: really weird and not general to program with +=, -=, etc. rather than =

Reversible Computer Engineering and Architecture

Carlin Vieri
MIT Artificial Intelligence Laboratory

Tom Knight: Committee chairman Gerald Sussman, Gill Pratt: readers

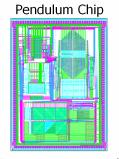
Pendulum Reversible Processor

- #200,000 Transistors
- **# 18 Instructions**
- #3-phase SCRL
- **#** 50 mm² in HP14
- 180 Pins

△32 power supplies

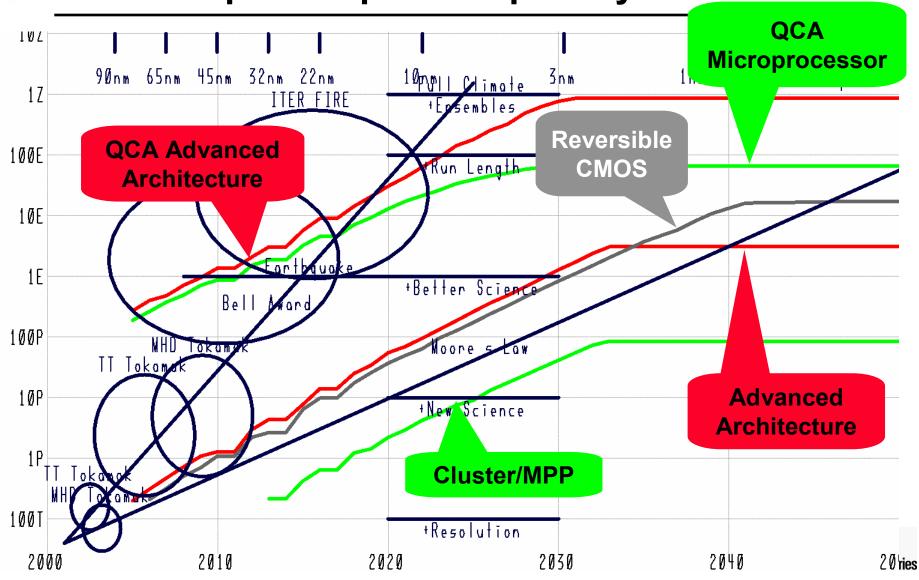
2 Person years for schematics and layout

PhD Thesis Defe





Supercomputer Expert System



Other Approaches to Extreme Computing

- Other fairly normal devices
 - Ballistic Y junction, parametric quantron
- Nanotechnology
 - New technologies are easy to propose when you can do atom-by-atom assembly. Helical logic, Carbon nanotube Y junctions, rod logic, ...
- Use the third dimension
 - Chips are 1cm x 1cm x 2 nm on .2 cm centers
 - Increase the 2 nm dimension!
- Coherent quantum computing





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Conclusions

- A review of supercomputer applications reveals a continuum up to 1 Zettaflops
- A review of "the physics of computation" reveals a progression of technologies offering progressively more performance for progressively more development effort
 - with no theoretical upper bound
- Integrating the ideas (with an expert system) suggests they could work together in a supercomputer
 - This is not the same as proving the ideas right!





- Don't believe me? Believe the Experts
- Workshop Agenda October
 - Applications session Climate expert Phil Jones
 - Advanced Architectures PIM expert Peter Kogge
 - Limits of Current Architectures Me
 - Limits Panel I: Limits of Current Technology
 - New Logic Reversible Logic Expert Michael Frank
 - New Devices Quantum Dot Developer Craig Lent
 - Limits Panel II: Opportunities with Innovation



Where To Go Next II: Roadmap

